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Comparative life-cycle assessment of uranium extraction processes

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ABSTRACT

This study assessed the environmental impacts of uranium extraction through three different mining process namely open-pit, underground, and in-situ leaching. The study is carried out through life-cycle impact assessment by using the International Reference Life Cycle Data System (ILCD) method, for 14 significant impact categories; the major categories with significant results are ionizing radiation, climate change, human toxicity, ecotoxicity, and eutrophication. Impact assessment through the Cumulative Energy Demand (CED) method is also carried out to assess the usage of renewable and non-renewable sources of energy in uranium extraction processes. All analysis is carried out for 1 kg uranium production through three different processes by using heavy fuel and diesel as the energy source. The comparative impact-assessment results for the open-pit mining method, underground mining, and in-situ leaching mining methods are presented and discussed in detail. Furthermore, a sensitivity analysis has been carried out to rationalize the linear relationship between the materials or fuels responsible for environmental impacts and sustainability. Three different scenarios are assessed including the base case scenario of the uranium extraction process. Sensitivity analysis results reveal the effect of fossil fuel based energy generation sources is the primary factor for causing environmental impacts during the uranium extraction routes.

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1. Introduction

Uranium is the heaviest metal naturally found in the earth's crust which is used as a nuclear fuel throughout the world. It is a radioactive, ductile and dense metal which forms uranium oxide when it comes in contact with air. It is used widely for producing nuclear energy through atomic chain reactions, making shields in bullets or missiles and producing fertilizers. Among the various natural isotopes of uranium available on the earth, the uranium 238 isotope constitutes more than 98%, while the rest is the uranium-235 isotope. The typical form of uranium found in the mines is uranium oxide in a 3 g per tonne concentration. To be an economically viable extraction site, the concentration must be 300 mg/kg (Mudd and Diesendorf, 2010).

As a power generation source, nuclear fuel has a range of economic benefits accompanied by environmental benefits. First of all, it offers a competitive fuel price considering the capital cost of the plant for power generation, despite a costly licensing system. In comparison with coal or natural gas, nuclear fuel only comprises 15% of the operating costs. Secondly, nuclear fuel is a low-carbon power generation source. However, there were some atomic accidents with detrimental health effects: the Chernobyl and Fukushima nuclear accidents, for example, that caused some devastating effects on environment and human health (Calder, 2014).

Uranium oxide is a source of nuclear power with emissions lower than fossil-fuel based energy generation systems (Ashley et al., 2015; Koltun, 2014; Lenzen, 2008; Mudd and Diesendorf, 2010; Mutchek et al., 2016; Norgate et al., 2014; Poinssot et al., 2014; Warner and Heath, 2012). More than four hundred atomic reactors have been operating throughout the world for electricity generation since 2012; which necessitates driving the uranium mining system towards a more sustainable and eco-friendly extraction system (Haque and Norgate, 2014; Parker et al., 2016; Vintró et al., 2014).

Due to the recent surge in the usage of uranium around the world, environmental impacts of nuclear-fuel mining technologies should be assessed thoroughly to ensure sustainability during the electricity generation from nuclear sources. To ensure sustainability of uranium extraction technologies from the manufacturer's perspective, it is indispensable to perform an environmental-effects assessment throughout the entire life-cycle of the uranium manufacturing process. The life-cycle environmental emissions of

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nuclear power generation are dependent on the uranium mining technologies. The source of electricity used for the uranium extraction process could, accordingly, contribute to environment-friendly nuclear fuel generation (Hudson et al., 1999; Lesage et al., 2008; Long, 2011).

Life-cycle assessment is a powerful environmental-impact assessment tool that is used for calculating the impacts of manufacturing technologies on various categories of human health, ecosystems, and resources of the environment (Curran, 2012; Henkel AG & CO. KGAA, 2008). This paper will address the life-cycle environmental-impact assessment for three different mining process of uranium extraction: open-pit, underground, and in-situ leaching. Section 2 gives an overview of uranium extraction techniques, through the mining and milling operations. Section 3 describes the global producers of uranium, their production capacity by year, location, and the current scenario of uranium mining in Australia. Section 4 describes the sustainability issues about uranium mining in Australia that are reported from open literature, as Australia has the highest deposit of uranium mining throughout the world. Section 5 describes the materials and methods with the details of four stages of life-cycle assessment. Section 6 discusses the analysis results in the context of comparative impact assessment based on the ILCD method, the CED method, and sensitivity analysis. Section 7 concludes with the summary of analysis results and recommendations for the future to reduce the environmental effects from uranium extraction processes.

2. Uranium mining

The mining technologies that are used in extracting uranium are broadly classified in three ways: in-situ leaching/solution mining, open-pit and underground mining. Underground mining techniques were the most common one during the early years of uranium extraction. In later years, this contribution decreased noticeably with the invention of the in-situ leaching process. The World Nuclear Association (WNA) states that 48% of the total uranium production comes from in-situ leaching mines. Table 1 provides a brief summary of current uranium extraction methods.

In the open-pit mining method, mining involves drilling and blasting, excavation, haulage, and sorting. The milling operation constitutes of crushing and grinding, leaching, washing, clarifying and filtering, solvent extraction, precipitation and wet-cake drying and calcination. The scope of this process covers the production of uranium yellowcake during the operation of an open-pit uranium mine, from resource extraction to the transportation from the mill to the conversion facility. After mining the finely ground uranium, it goes through a conventional chemical-based extraction process which requires leaching, concentration, and purification. The leaching technique is dependent on the uranium ore grade. It might be dynamic lixiviation (average recovery of 95% of uranium) or static lixiviation (typical improvement of 60–80% of uranium).

The in-situ leaching method is used in some mining sites and involves an entirely different process from the previous ones (ELaw, 2014). The next step is to concentrate the uranium through ion exchange or extraction. Chemical precipitation is done later after concentrating the uranium oxide which contains impurities. This product is known as yellowcake. Finally, yellowcake is heated to get rid of ammonia and to make 97% pure uranium oxide. Then the yellowcake is transferred to purification or other processing facilities through ship, truck or train depending on the mine facilities. Purification is necessary for further enrichment of uranium to modify it into solid uranium oxide which is used as the nuclear fuel in nuclear power generation units. After the uranium enrichment process, depleted uranium waste is produced; which can be further processed to be used as an alternative nuclear fuel. In addition to this, large quantities of waste rock are produced that contain low-grade uranium (Lunt et al., 2007).

The advantage of in-situ mining is that it allows non-disturbed surface extraction of uranium as the process involves injecting reagents through a small diameter hole sink for mobilizing the minerals. Then the extracted solution is processed to recover the metals. Another significant advantage is that tailing storage is not required. Additionally, it never consumes massive amounts of water due to continuous recycling through the injected wells. Due to the benefits of in-situ leaching uranium mining methods, it might be expected that the environmental burdens would be significantly reduced; however, the re-injected fluid can potentially spread to other groundwater resources which could be dangerous (Mudd, 2000; Schwartz and Colman, 1998; Taylor et al., 2004). Fig. 1 shows the Uranium mining process flowchart.

3. Global producers of uranium

Table 2 presents the operating mines throughout the world, responsible for 68% of uranium production. Fig. 2 illustrates the total output of uranium from the entire world. Kazakhstan is the top producer of uranium with 39.5% of the total global production. As shown in Table 2, the seven major mines from Kazakhstan produces in total 25% of the global production; all of them follow in-situ leaching mining operations. Australia produces only 8% of the total world's production, while the recoverable resource amount is 29%. Canada is the second largest producer of uranium with a total production capacity of 22% of the entire world. Table 2 only represents the major uranium mines and their production share, while Fig. 2 depicts the total output from all the uranium mines in respective countries. So, the percentage values presented in Table 2 and Fig. 2 are different.

This 68% production of the total uranium in the world comes from 5 major uranium companies out of which KazAtomProm produces 21% and AREVA 13%, Cameco 17%, ARMZ produces 13% and Rio Tinto 4%. McArthur River mine (underground mining system) of Canada is the most abundant productive uranium mine in the world. Among the top 15 mines of the world, six mines are located in Kazakhstan, two in Canada, and two in Australia (Reichl et al., 2016; World Nuclear Association, 2014).

Table 1
Brief description of uranium extraction methods (World Nuclear Association, 2014).

Methods of Uranium Ore Mining	Description	World Production (%) by World Nuclear Association
Underground Mining	Vertical shafts or tunnels are used for drilling depending on the depth of deposit.	47
Open-Cut Mining	A large amount of overburden must be excavated to reach the uranium ore.	
In-situ Leaching	Vertical bore holes are used to introduce a leaching solution to further extract uranium from shallow deposits.	48
Recovery from mining of other materials	To recover uranium from other material mines, detailed analysis about the depth of overburden, depth of ore body, and inclination of ore body is required to choose which method would be economical.	5

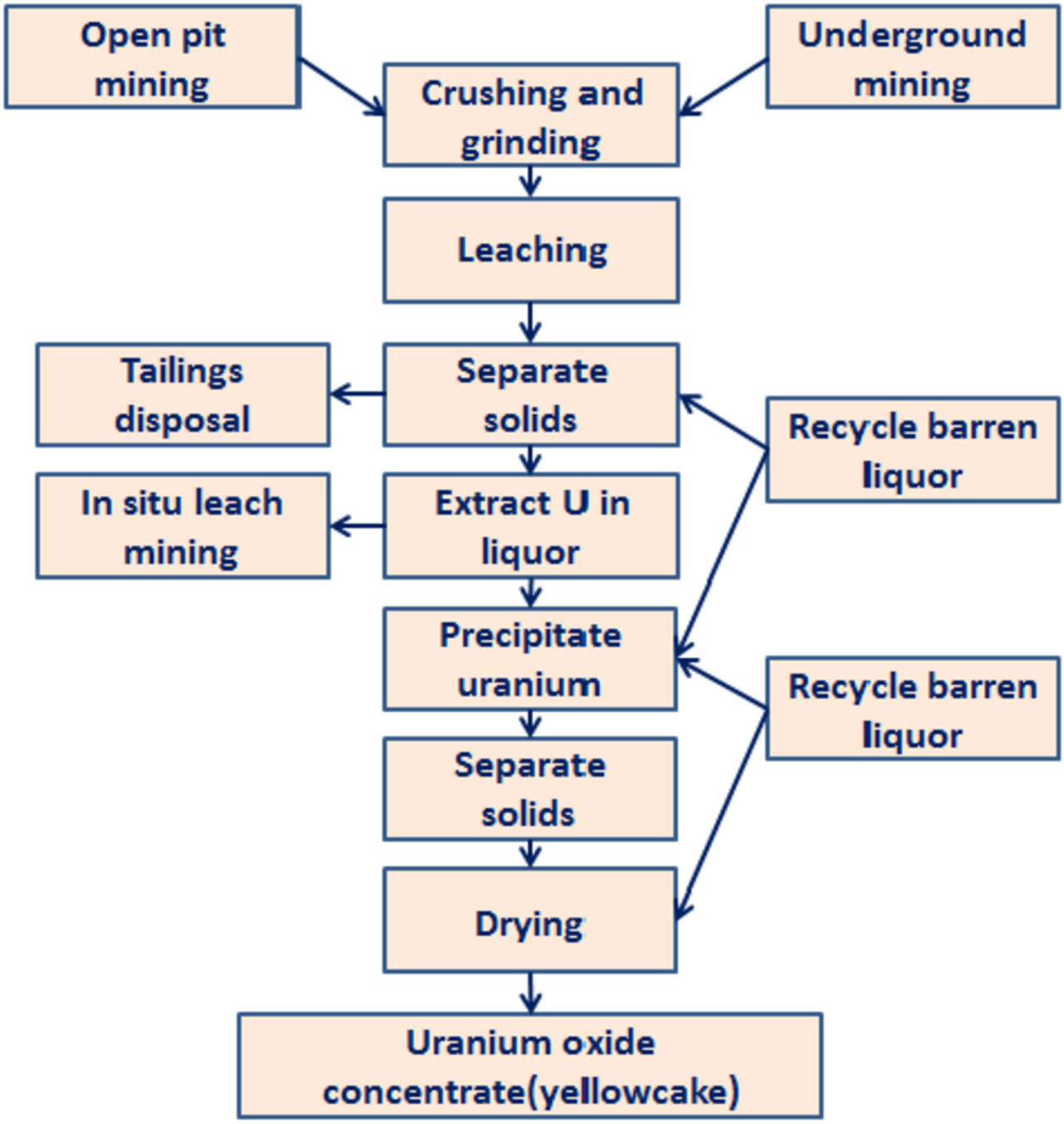


Fig. 1. Uranium mining process flowchart (Virginia et al., 2012; World-nuclear.org, 2013).

3.1. Uranium production in Australia

Australia currently holds the highest amount of recoverable uranium in the world. Primary export targets of Australian uranium resources are Belgium, Canada, China, Finland, France, Japan, South Korea, Spain, Sweden, United Kingdom and the United States. Over the last few decades, massive-scale uranium operating mines have been established and some of the current projects are expanding. Australia has about 85 uranium deposits throughout the continent of various sizes (Schwartz and Colman, 1998). More than 80% of these deposits are located in South Australia and can be recovered at low cost (Wilson and Fairclough, 2009). The Northern Territory holds the second position with 19% of Australia's uranium deposits, and the remaining 6% can be found in Western Australia. Among the world's top 20 most significant uranium deposits, seven are situated in Australia: Olympic Dam (SA), Jabiluka (NT), Ranger (NT), Yeelirrie (WA), Valhalla (QLD), Kimtyre (WA) and Beverley (SA). Fig. 3(a)–(c) show the Ranger mine, Olympic Dam and Beverley mine in Australia.

Uranium was first discovered in Australia in 1906, at Radium Hill in South Australia. Later, in the 1930s, uranium ore was mined at Mount Painter and Radium Hill. Olympic dam is the single largest uranium deposit in the world. The Beverley mine came into operation in the year 2000. The Four Mile uranium deposit was

Table 2
Top 15 uranium mines of the world.

Country	Major Mine Name	Owner Company	Mine Type	Reserve amount in Tonne uranium	% of World production
Kazakhastan	Torkuduk and Myunkum	Katco JV/AREVA	In-situ Leaching	4002	6
	Budenovskoye 2	KazaAtomProm, Uranium One	In-situ Leaching	2081	3
	South Inkai	Uranium One	In-situ Leaching	2056	3
	Inkai	Inkai JV/Cameco	In-situ Leaching	2291	4
	Central Mynkuduk	KazaAtomProm	In-situ Leaching	2010	3
	Budenovskoye 1, 3 & 4	KazaAtomProm, Uranium One	In-situ Leaching	1743	3
	Kharasan 2	Baiken-U	In-situ Leaching	1838	3
Canada	McArthur River	Cameco	Underground	6945	11
	Cigar Lake	Cameco	Underground	6666	11
Australia	Olympic Dam	BHP Billiton	Underground/by-product	3233	5
	Ranger	ERA (Rio Tinto 68%)	Open pit	1994	3
Namibia	Rossing	Rio Tinto (69%)	Open Pit	1569	2.5
	Langer Heinrich	Paladin	Open Pit	1893	3
Niger	Somair	AREVA	Open Pit	2164	4
Russia	Priargunsky	ARMZ	Underground	1873	3
Total				42367	68%

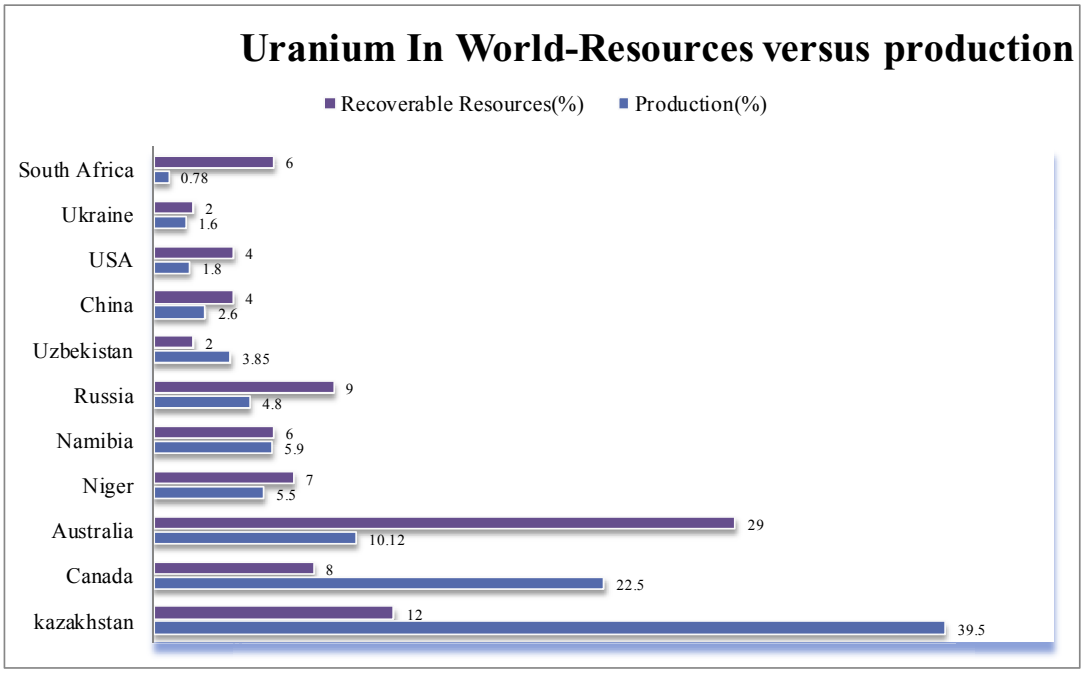


Fig. 2. World uranium resources and production by country (World Nuclear Association, 2014).

Fig. 3. (a), 3(b) & 3(c). Ranger mine, Beverley mine, and Olympic dam.

discovered in 2005 and processing started in 2015. In 2011, in-situ recovery began on the Honeymoon uranium mine. Another notable uranium mine in Australia is the Ranger uranium mine in the Northern Territory. According to the World Nuclear Association report July 2017, five new uranium mines are going to be in operation by the end of 2018. Two of those are located in Australia which are Mulga Rock and Wiluna (Mudd, 2002; Simons and Firth, 2011). Fig. 4 shows a uranium mines map of Australia (World Nuclear Association, 2014).

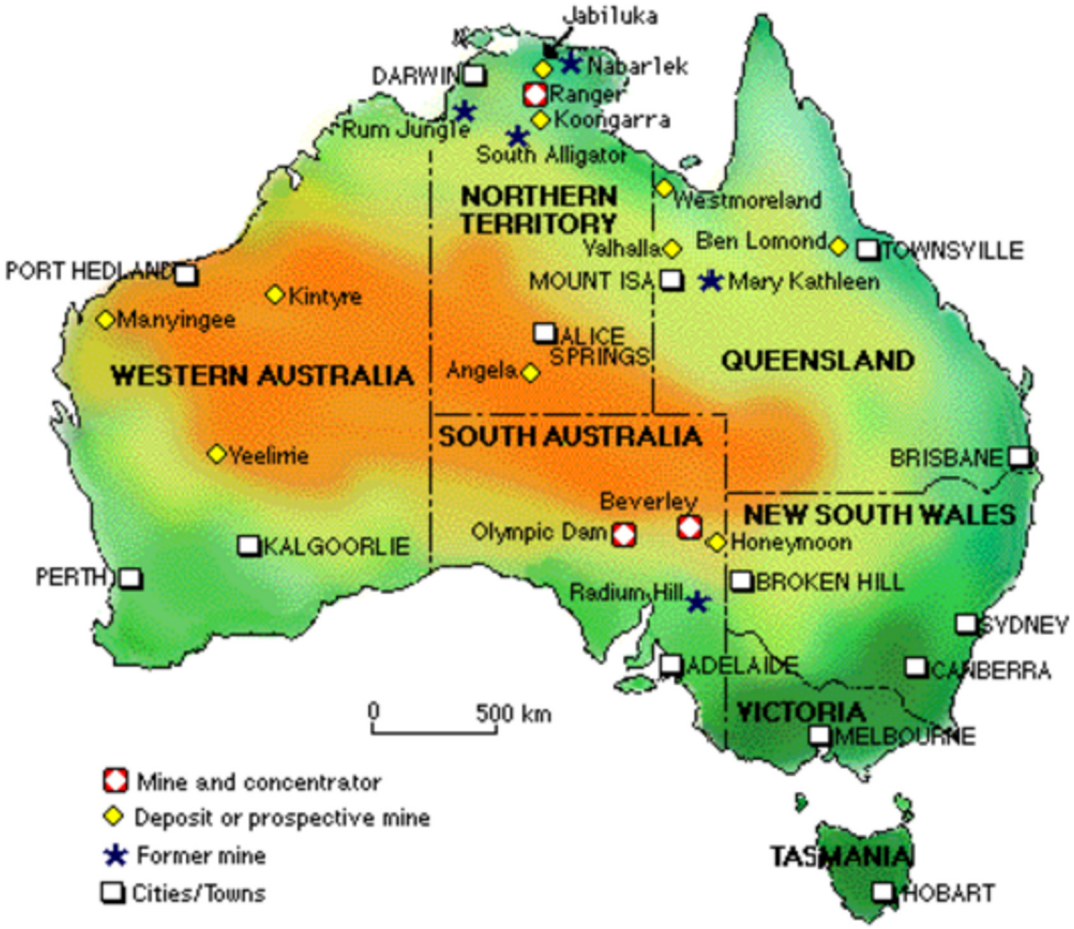


Fig. 4. Uranium mines map of Australia (World Nuclear Association).

4. Sustainability issues of uranium mining

Uranium mines should satisfy the environmental-risk-management criteria, under the categories of human health, environment, land uses and water resources, to be commissioned as operating mines. In order to align with sustainability policies. The hazardous effects and emissions from these uranium mines should be assessed throughout their entire life-cycle (EPA, 2006; Taylor et al., 2004). Over the last decades, tailings and waste management in uranium mills have been a focus, and regulations are also changing for environmental hazards and radiological risks. To reveal the regulatory changes, an examination of history is required. During the 1950s, wastes from mines were discharged to lowland areas constituting rivers and water resources. These had a significant effect in wet seasons as the water quality decreased and erosion occurred in wet regions. In arid regions, uranium mills' radioactive and mineral wastes were managed through water dams. During the 1970s regulations were introduced to transfer the tailings back into the mined pit as soon as possible after uranium extraction, by using these ground dams.

In addition to producing radioactive wastes, these large amount of wastes pose a health threat towards the community living close to uranium mines and mills. The process of making yellow-cake involves highly toxic substances. These radioactive tailings could contaminate the groundwater resources through rain and erosion. Contamination could also occur through insufficient covering of wastes and tailings. From the heaps of materials, wind could blow radioactive particles away from the mines. Wind erosion also occurs due to the inadequate coverage of tailings. The amount of water required for uranium mining is huge, and it is returned to groundwater resources like lakes and rivers. This mixture of fresh groundwater and water used in the radioactive processing has direct detrimental health effects, also damaging the ecosystems which it encounters. This reduces freshwater availability and at the same time causes significant risks to the animals and plants due to radioactivity. If uranium mines are abandoned, these mines are flooded with water, which also implies contamination of fresh water. Leaking from all these sources may cause harm to respiratory systems in the human body, lung cancer, leukemia, stomach cancer and congenital disabilities (Mudd, 2000, 2009; 2008; Northey et al., 2013; World Nuclear Association, 2014). Attention should also be paid to the use of radioactive byproduct metals for several non-mining purposes, such as the manufacture of kitchen utensils (in which the health risks associated with the use of these radioactive metals remain) (Mudd, 2006).

At earth's surface, on all continents, there are some levels of natural radiation in the soil, water, air, flora, and fauna. Uranium-238, uranium-235 and their daughter products are present in all rocks and soil. These natural radionuclides are also naturally present in the lower atmosphere (dust from the soil) along with radon-222 which permanently emanates from the rocks and soil. They are also present in surface and underground waters in contact with this soil and rocks as well as in the crops, flora, and fauna and therefore in the food chain. The radiation emitted by these radionuclides is called the natural background radiation. When uranium ore is buried underground – at a depth of few tens or even a few

hundreds of meters – the radiation levels at the surface of the soil remain low and usually have the same order of magnitude as natural radiation levels. Some areas of a limited extent can be found where the ore reaches the ground surface. Otherwise, the protection offered by the soil is usually sufficient to reduce the risks for people living in the area. Indeed, alpha and low-energy beta particles are stopped by a thin layer of soil (much less than 1 cm). Even penetrating gamma radiation do not cross a layer of soil only a few meters deep. Most of the radon gas remains trapped inside the soil because of its short half-life (3.8 days) and many of the gas atoms will disintegrate inside the soil during their migration before reaching the biosphere.

When uranium is mined, uranium ores which high uranium content are brought to the surface. A typical ore with a uranium concentration of 0.2% has a uranium-238 activity of about 25,000 Bq/kg. The total activity calculated including all the uranium-238 daughter products and the uranium-235 decay chain, therefore, exceeds 360,000 Bq/kg, while the mean activity of the earth's crust is below 2000 Bq/kg. Such material should be managed with a great deal of caution due to the risks of exposure to ionizing radiation. (Haque et al., 2014; Northey et al., 2013, 2016; Sonter et al., 2014).

5. Materials and method

Life-cycle assessment or LCA is a systematic tool for analyzing and calculating the environmental effects and impacts caused by the manufacturing of a product, process or activity throughout its entire life-cyclefrom the cradle to the grave, cradle to gate, and gate to grave. LCA works through identification and quantification of input materials, energy and resources and output products and emissions to the environment such as air, water or soil. The LCA methodology in this study is based on the International Organization for Standards (ISO) 14040, that follows four mandatory stages which are required to be completed: goal and scope definition, life-cycle inventory, life-cycle impact assessment, and interpretation and recommendation of the inventory and results (Durucan et al., 2006; Onn and Woodley, 2014). SimaPro software version 8.5 is used for analysis and comparison for different uranium extraction routes are presented in details. The datasets are considered from EcoInvent databases, Australian Life cycle Inventory database (AusLCI) and several literature resources.

5.1. Goal and scope definition

The goal of this study is to assess the life-cycle environmental

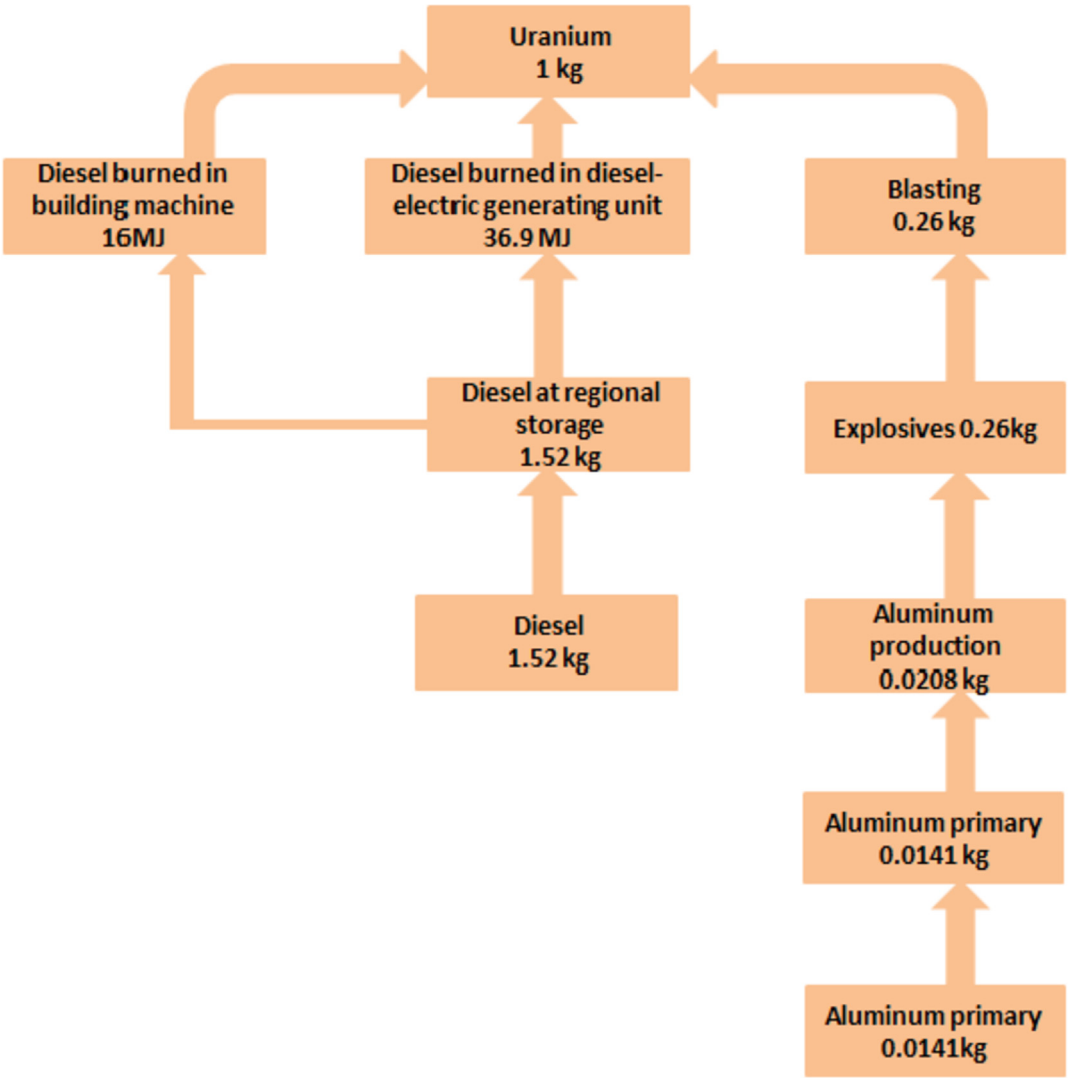


Fig. 5. Material flow sheet for uranium extraction process - open pit mining.

impacts of uranium extraction routes: open-pit mining, underground mining, and in-situ leaching. This study also compares their life-cycle assessment results to identify the most sustainable uranium extraction process. The life-cycle assessment is done under a cradle-to-gate perspective for those three processes, which considers from raw materials acquisition to the packaging and delivery of the final product (Drielsma et al., 2016; Santero and Hendry, 2016). Fig. 5, Fig. 6, and Fig. 7 sequentially illustrate the energy and heat consumption in different stages of the uranium extraction process, for open-pit mining, underground mining, and in-situ leaching respectively. The functional unit assessed in this study is 1 kg of uranium, which is the representative of the unit amount of reference flow (Ranängen and Lindman, 2017; Raugei and Ulgiati, 2009).

Lenzen et al. thoroughly evaluated the life-cycle energy balance of nuclear power generation in Australia. They also compared the energy balance of the nuclear fuel cycle with the energy balance of other renewable and non-renewable power-generation sources (Lenzen, 2008). Parker et al. worked on life-cycle greenhouse-gas emission calculations and assessments of uranium mining and

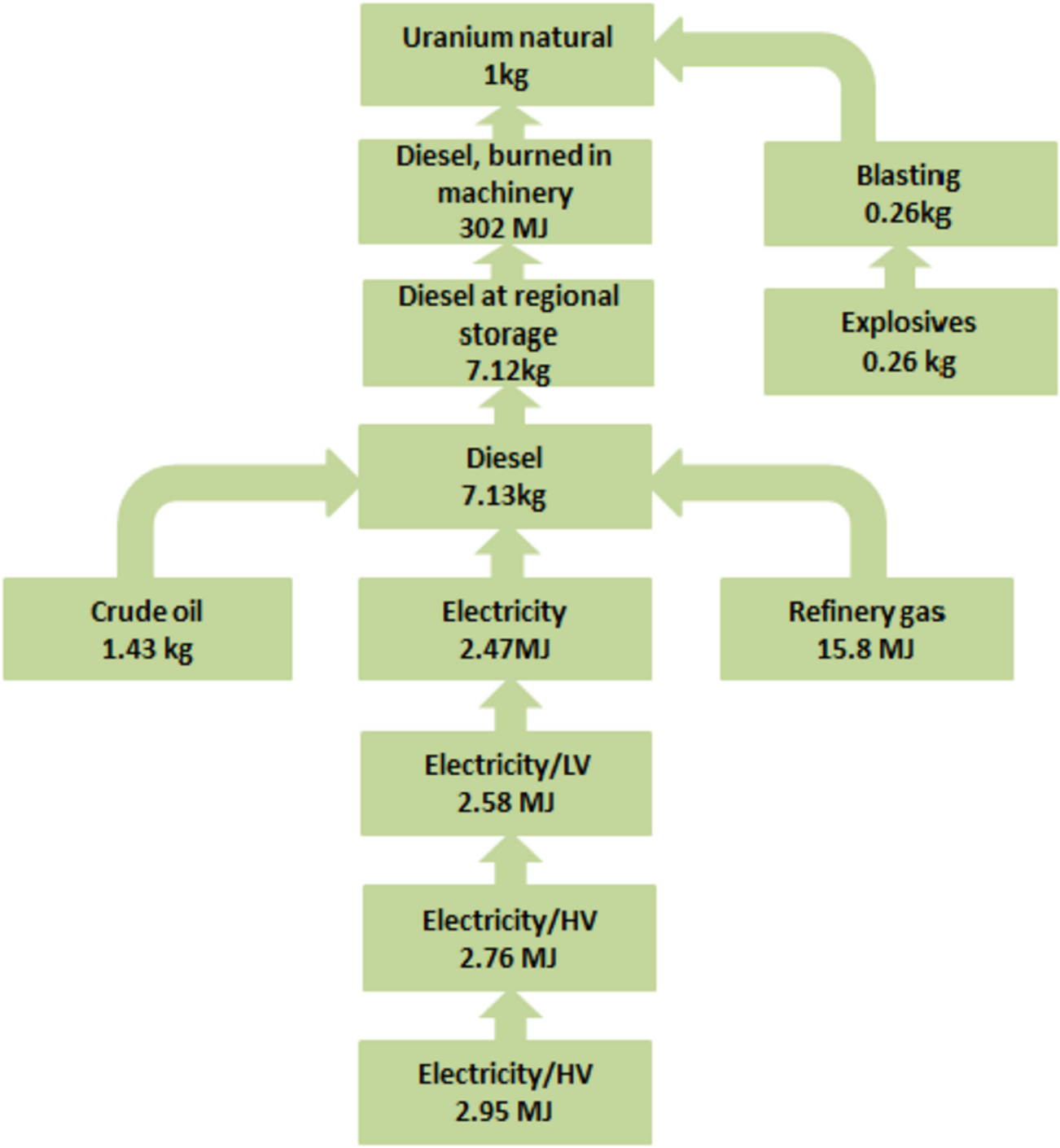


Fig. 6. Material flow sheet for uranium extraction process - underground mining.

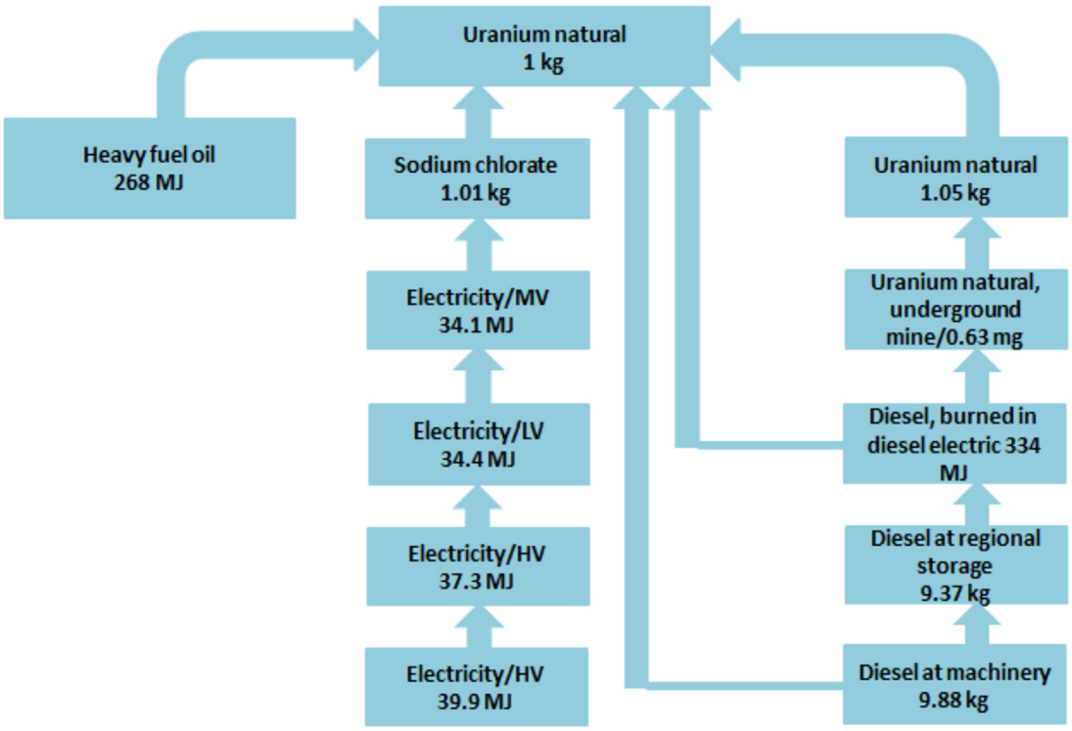


Fig. 7. Material flow sheet for uranium extraction process - in-situ leaching mining.

milling in Canada (Parker et al., 2016). Haque et al. analyzed greenhouse gas emissions from the in-situ-leaching based uranium extraction process and then compared this with the conventional uranium mining process (Haque and Norgate, 2014; Norgate et al., 2014). Moran et al. outlined the sustainability of mining and energy with the focus on future mining challenges, sustainability framework, and mining management aspects (Moran et al., 2014). Pellegrino et al. worked on climate-change accounting in Australia and explored the critical factors of the Australian mining industry regarding climate change (Pellegrino and Lodhia, 2012). Schneider et al. proposed a new research framework for energy, land, and water use in the uranium mining and milling industries (Schneider et al., 2013). Tost et al. reviewed the state-of-the-art environmental sustainability considerations in mining, mostly non-LCA (Tost et al., 2018). Tuusjarvi et al. outlined the Finnish mining industries' developmental scenario and considered the scenario analysis concerning sustainability. Mudd et al. carried out comprehensive research in several papers based on sustainability assessment of uranium mining, in-situ-leaching mining, radiation hazards and emissions from uranium mining (Mudd, 2000, 2009; 2008, 2007; 2002; Mudd and Diesendorf, 2010, 2008; Northey et al., 2016). Haque et al. assessed the life-cycle impacts of in-situ-leaching uranium mining and effects of uranium ore grade in their works (Haque and Norgate, 2014; Norgate et al., 2014). Table 3 summarizes the literature survey of sustainability research on uranium mining technologies.

So far, life-cycle impact assessment of uranium mines, comparing the relative benefits of open-pit mining, underground mining, and in-situ leaching has not been reported in the open literature. Furthermore, there is no detailed research on an environmental impact comparison of uranium production methods. The current work thus serves as a vital resource to provide such invaluable information.

5.2. Life cycle inventory

This stage identifies the materials, resources and energy inputs, output products, wastes and emissions of uranium production and quantifies their respective amounts per unit process included in the system boundary for life-cycle assessment. For carrying out life-cycle assessment, the second stage is to collect the inventory data. The inventories for the uranium extraction process vary

Table 3
Literature survey on sustainability research on uranium mining technologies.

Literature	Analysis Method	Description
Johnston et al.(Johnston and Needham, 1998)	Non-LCA	Environmental protection near the area of Ranger mine, Australia, provides summary of all biological monitoring methods.
Mudd et al.(Mudd, 2000)	Non-LCA	A detailed and comprehensive discussion on change of ionizing radiation and radionuclide releases from former and operational projects on uranium mining in Australia.
CSIRO report (Taylor et al., 2004)	Non-LCA	Research and review based on the fact that acid in-situ leaching would contaminate groundwater.
Mudd et al.(Mudd, 2008)	Non-LCA	Researches on energy, water consumption and carbon emission in respect of uranium production.
Mudd et al.(Mudd and Diesendorf, 2008)	Non-LCA	Detailed compilation and analysis of radon releases in Australia.
Mudd et al.(Mudd and Diesendorf, 2010)	Non-LCA	Comprehensive insight into uranium mining and its economic resources.
Haque et al.(Haque and Norgate, 2014)	LCA	Life-cycle assessment of in-situ-leaching uranium mining methods collected the global data and integrated Australian electricity mix.

among different companies, countries, and regions. This variation can eventually affect the impact-assessment results. The main difference among the inventories here is their raw materials, energy inputs, fossil fuels and electricity consumption. The input flows can be defined as the raw materials, energy and resources, and are given for 1 kg of uranium yellowcake production. Fig. 8 shows the system boundary for life-cycle assessment of uranium extraction routes. The system boundary encloses uranium ore, raw materials, fuels, energy, electricity, inorganic and organic chemicals, and transportation. On the other hand, uranium yellowcake (1 kg) and waste emission are considered as the outputs (Durucan and Korre, 2003, 1998; Heard, 2017). Table 4 provides a life-cycle

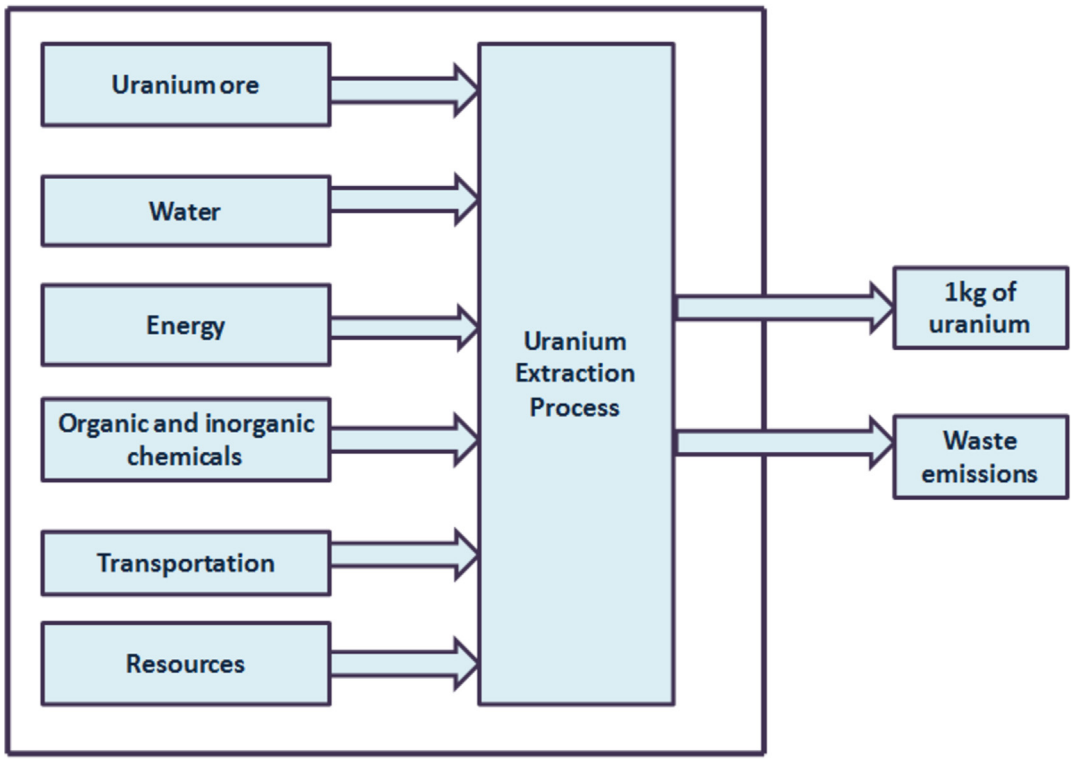


Fig. 8. System boundary of uranium extraction process used in this work.

Table 4
Life-cycle inventory datasets - inputs for uranium extraction process (datasets are collected from EcoInvent and AusLCI databases).

Inputs	From	Open-pit mining method	Underground mining method	In-situ-leach mining method	Unit
Transformation, from unknown	Nature	0.182	0.005	0.018	m^2
Transformation, to mineral extraction site	Nature	0.182	0.005	0.018	m^2
Transformation, from industrial area	Nature	0.182	0.005		m^2
Transformation, to unknown	Nature	0.182	0.005		m^2
Occupation, mineral extraction site	Nature	4	0.1	1.96	m^2a
Uranium, in ground	Nature	1.05	1.05	1.05	kg
Water, unspecified natural origin	Nature	6	0.1	1	m^3
Diesel, burned in building machine	Materials/fuel	16			MJ
Diesel, burned in diesel-electric generating set	Materials/fuel	36.5	300	176	MJ
Blasting	Materials/fuel	0.26	0.26		kg
Transport, lorry >16t	Materials/fuel	7.23	0.23		tkm
Transport, freight, rail	Materials/fuel	1.37	1.37		tkm
Uranium	Materials/fuel	6.17E-8	0.000000278	0.000000135	p
Heavy fuel oil, burned in electric furnace	Materials/fuel			264	MJ
Ammonia, liquid	Materials/fuel			0.9	kg
Ammonium sulphate	Materials/fuel			0.106	kg
Chemicals inorganic	Materials/fuel			0.26	kg
Chemicals organic	Materials/fuel			0.315	kg
Ethylenediamine	Materials/fuel			0.012	kg
Soda, powder	Materials/fuel			2.5	kg
Sodium chlorate, powder	Materials/fuel			1	kg
Sodium chloride, brine solution	Materials/fuel			2.5	kg
Sodium hydroxide, 50% in H_2O production mix	Materials/fuel			0.026	kg
Sulfuric acid, liquid	Materials/fuel			35	kg
Transport, lorry >16t, fleet average	Materials/fuel			6.3	tkm
Transport, freight, rail	Materials/fuel			32	tkm

inventory datasheet for input flows (materials and their respective quantities). Table 5 presents life-cycle inventory datasheet for output flows (elements and their respective amounts).

5.3. Life cycle impact analysis

The life cycle impact assessment in the analysis phase is based on different methods such as ILCD, TRACI, CML, ReCiPe, etc. This phase assesses the impacts of the process/system/activity on human health, ecosystem, water, land, and economy. Furthermore, there are optional additions for normalization, grouping or weighting of the indicator results and data-quality analysis techniques. In the present study, first of all, the life-cycle impact analysis (LCIA) is done using International Reference Life Cycle Data System (ILCD) method, which is a standard method based on ISO 14040 and developed by the European Commission Institute for Environment and Sustainability. This LCIA method considers 16 significant midpoint impact categories including ionizing radiation. Ionizing radiation is a significant impact category during uranium extraction that provides valuable information that can be assessed during the LCIA using the ILCD method. (Adiansyah et al., 2017; Sonter et al., 2014). In the second stage, the Cumulative Energy

Table 5
Life-cycle inventory datasets-outputs for uranium extraction process (datasets are collected from EcoInvent and AusLCI databases).

Outputs	To	Quantity in Open-pit mining method	Quantity in underground mining method	Quantity in in-situ-leach mining method	Unit
Uranium natural	Product	1	1	1	kg
Aldehydes, unspecified	Air			0.00088	kg
Ammonia	Air			0.0017	kg
Beryllium	Air		0.00000098		kg
Cadmium	Air		0.000002		kg
Lead	Air		0.00002	2	kBq
Polonium-210	Air			W	kBq
Nitrogen oxides	Air			0.017	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	Air			0.11	kg
Particulates, > 10 μm	Air	0.056	0.033	0.22	kg
Particulates, > 2.5 μm, and <10 μm	Air			0.00088	kg
Sulfur dioxide	Air			0.00023	kg
Zinc	Air		0.00002		kg
Radon-222	Air	13000	1000000	150000	kBq
Radium-226	Air		13	1	kBq
Uranium alpha	Air	0.094	23		kBq
Thorium-230	Air			1	kBq
Uranium-234	Air			2.9	kBq
Uranium-235	Air			0.14	kBq
Uranium-238	Air			2.9	kBq
Aluminum	Water	0.0031	0.023	0.35	kg
Ammonium, ion	Water	0.0085	0.065	0.072	kg
Arsenic, ion	Water	0.000093	0.000068	0.000081	kg
Barium	Water	0.0019	0.0014	0.00011	kg
Beryllium	Water			0.000014	kg
Cadmium, ion	Water	0.000093	0.000068		kg
Calcium, ion	Water			0.54	kg
Chloride	Water	0.86	0.6	0.52	kg
Chromium, ion	Water			0.00096	kg
Copper, ion	Water			0.0002	kg
Cyanide	Water			0.00000088	kg
Fluoride	Water			0.00066	kg
Hydrocarbons, unspecified	Water			0.0035	kg
Iron, ion	Water	0.034	0.11	0.1	kg
Lead	Water	0.018	0.013	0.0015	kg
Magnesium	Water	0.11	0.082	0.01	kg
Manganese	Water	0.069	0.00075	0.015	kg
Molybdenum	Water	0.0016	0.018	0.0019	kg
Nickel, ion	Water			0.0001	kg
Nitrate	Water	0.0021	0.041	0.0087	kg
Phosphate	Water			0.00022	kg
Selenium	Water	0.00019	0.00041	0.0016	kg
Silver, ion	Water			0.00000088	kg
Sodium, ion	Water		4.7	0.04	kg
Sulphate	Water	48	3.4	1.6	kg
Sulfide	Water			0.000044	kg
Suspended solids, unspecified	Water	2.1	0.15		kg
Titanium, ion	Water			0.0012	kg
Vanadium, ion	Water	0.0065	0.0048	0.000018	kg
Zinc, ion	Water	0.0012	0.00089	0.00052	kg
Carbonate	Water			0.036	kg
Radium-226	Water	5000	1600	1	kBq
Thorium-230	Water	460	300	150	kBq
Uranium alpha	Water	220	310	4.85	kBq
Uranium-234	Water			0.3	kBq
Uranium-238	Water			4.85	kBq
Tailings, uranium milling	Waste			0.25	M3

Demand method is also utilized to assess the environmental effects based on the energy consumption in different stages/materials. The forms of energy considered here are renewables, fossil fuels, biogas, nuclear, and others. In the third stage, sensitivity analysis is carried out to identify the critical manufacturing material/process steps responsible for environmental emissions to enhance the efficiency towards sustainability (Awuah-Offei and Adekpedjou, 2011; PE International, 2014). Fig. 9 graphically represents the methodology of life-cycle assessment considered in this research.

5.3.1. Open-pit mining

Table 6 describes the quantified results of LCIA for open-pit mining. Among the 14 major impact categories presented here, ionizing radiation has the most significant impact of 178.55 kBq U235 eq. The second-most impactful category is human toxicity (non-cancer effects) at 2.56E-06 CTUh. Thirdly, water resources depletion impact is higher than the other impact categories which is 0.9744 m^3 water eq. From the other significant categories, the climate-change effect is 6.27 kg CO_2.

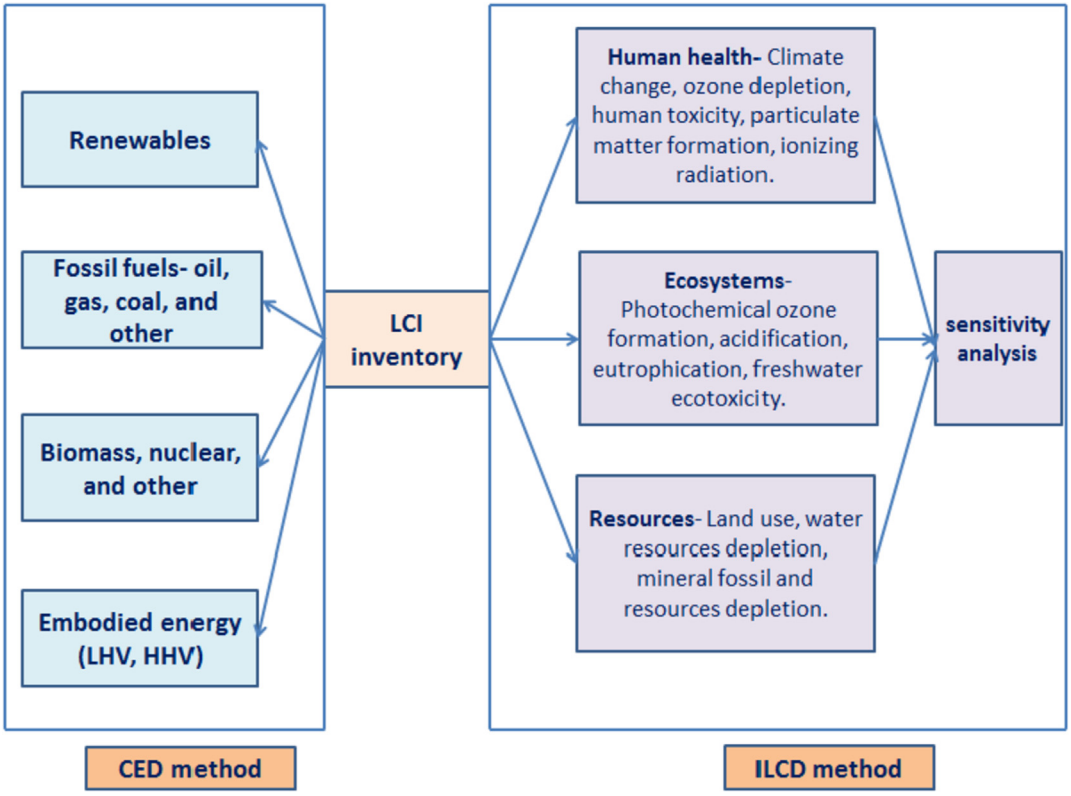

Renewables
Fossil fuels- oil, gas, coal, and other
Biomass, nuclear, and other
Embodied energy (LHV, HHV)
LCI inventory
Human health- Climate change, ozone depletion, human toxicity, particulate matter formation, ionizing radiation.
Ecosystems- Photochemical ozone formation, acidification, eutrophication, freshwater ecotoxicity.
Resources- Land use, water resources depletion, mineral fossil and resources depletion.
sensitivity analysis
CED method
ILCD method

Fig. 9. LCIA methodology of this research.

Table 6
Life cycle impact analysis results for open-pit mining using ILCD method.

Label	Unit	Total	Uranium natural, at open pit mine	Diesel, burned in building machine	Diesel, burned in diesel-electric generating set	Blasting	Transport, lorry >16t, fleet average	Transport, freight, rail
Climate change	kg CO_2 eq	6.273	0	22.19	50.1034	12.34	14.8	0.556
Ozone depletion	kg CFC-11 eq	7.02E-07	0	24.9154	55.4327	2.779	16.4298	0.44
Human toxicity, non-cancer effects	CTUh	2.56E-06	96.34	0.5067	1.715	1.084	0.338	0.012
Human toxicity, cancer effects	CTUh	1.68E-08	36.55	1.22	2.68	58.88	0.61	0.038
Particulate matter	kg PM2.5 eq	0.00857	0	21.26	35.59	40.287	2.671	0.183
Ionizing radiation HH	kBq U235 eq	178.55	99.99	1.58E-05	3.51E-05	6.81E-05	1.04E-05	2.8E-07
Ionizing radiation E (interim)	CTUe	1.15E-09	0	2.123	4.647	91.817	1.374	0.0371
Photochemical ozone formation	kg NMVOC eq	0.189	0	10.438	29.93	54.752	4.62	0.24
Acidification	molc H+ eq	0.18	0	8.4	25.31	62.62	3.45	0.19
Terrestrial eutrophication	molc N eq	0.907	0	8.0263	24.25	64.41	3.1	0.19
Freshwater eutrophication	kg P eq	4.38E-06	0	6.57	10.17	80.148	2.812	0.283
Marine eutrophication	kg N eq	0.0722	9.807	9.193	27.82	49.39	3.56	0.2208
Freshwater ecotoxicity	CTUe	12.065	95.467	0.583	1.30	2.212	0.423	0.0116
Land use	kg C deficit	78.424	99.714	0.0008	0.001	0.157	0.0005	0.125
Water resource depletion	m3 water eq	0.9744	99.74	0.047	0.104	0.067	0.0308	0.0011
Mineral, fossil & resource depletion	kg Sb eq	4.92E-14	0	10.625	23.15	59.19	6.84	0.18

Fig. 10 illustrates the life-cycle assessment results assessed through the ILCD method. From Fig. 10, in open-pit mining, based on the LCIA conducted using the ILCD method, diesel burned in machineries is the source of significant impacts for climate change, particulate matter, marine eutrophication, and water resource depletion. Diesel burned in the diesel-electric generating unit is responsible for climate change, ozone depletion, and ionizing radiation (interim). Uranium ore has effects on human toxicity (cancer), human toxicity (non-cancer), and ionizing radiation. Blasting is most impactful on sustainability that has an adverse effect in human toxicity (cancer effects), particulate matter, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, land use, water resource depletion, and mineral fossil and resources depletion.

5.3.2. Underground mining

Table 7 describes the quantified results of LCIA for underground mining. Among the 14 major impact categories presented here, ionizing radiation has the most significant impact at 1150.27 kBq U235 eq. The second most impactful category is human toxicity (non-cancer effects), at 4.08E-06 CTUh followed by water resources depletion impacts at 0.0252 m^3 water eq. Other notable impact category is the climate-change effect which is 26.67 kg CO_2 per kg of uranium production.

Fig. 11 illustrates the life-cycle assessment results assessed through the ILCD method. As the figure shows, diesel burned in the diesel-electric generating unit is responsible for climate change, ozone depletion, particulate matter, photochemical ozone formation, marine eutrophication, and ionizing radiation (interim). Uranium ore effects on human toxicity (cancer), human toxicity (non-

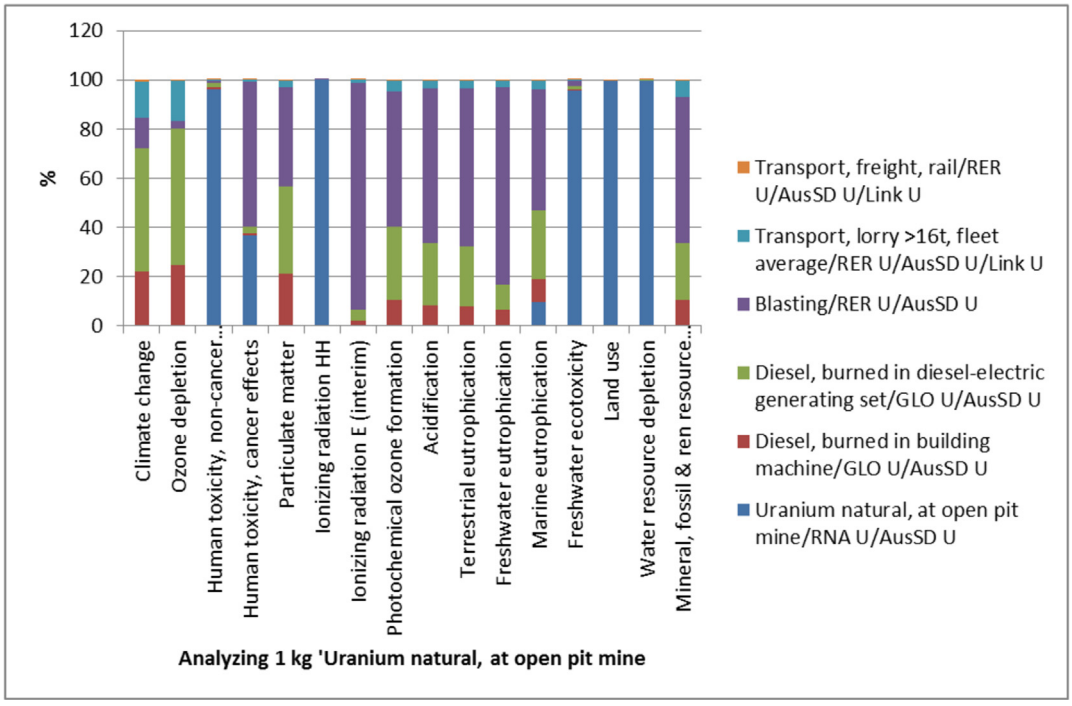


Fig. 10. Comparative life-cycle assessment results - open-pit mining.

Table 7
Life cycle impact analysis results for underground mining using ILCD method.

Impact category	Unit	Total	Uranium natural, at underground mine	Diesel, burned in diesel-electric generating set	Blasting	Transport, lorry >16t, fleet average	Transport, freight, rail
Climate change	kg CO_2 eq	26.67	0	25.83	0.77	0.029	0.034
Ozone depletion	kg CFC-11 eq	3.22E-06	0	3.20E-06	1.95E-08	3.67E-09	3.11E-09
Human toxicity, non-cancer effects	CTUh	4.08E-06	3.69E-06	3.61E-07	2.78E-08	2.76E-10	3.07E-10
Human toxicity, cancer effects	CTUh	1.90E-08	5.37E-09	3.71E-09	9.92E-09	3.28E-12	6.43E-12
Particulate matter	kg PM2.5 eq	0.028	0	0.025	0.003	7.28E-06	1.57E-05
Ionizing radiation HH	kBq U235 eq	1150.2	1150.27	0.0005	0.0001	5.90E-07	5.01E-07
Ionizing radiation E (interim)	CTUe	1.50E-09	0	4.40E-10	1.06E-09	5.03E-13	4.27E-13
Photochemical ozone formation	kg NMVOC eq	0.569	0	0.4655	0.103	0.0002	0.0004
Acidification	molc H+ eq	0.487	0	0.3745	0.112	0.00019	0.0003
Terrestrial eutrophication	molc N eq	2.39	0	1.8	0.58	0.0008	0.0017
Freshwater eutrophication	kg P eq	7.19E-06	0	3.66E-06	3.51E-06	3.92E-09	1.24E-08
Marine eutrophication	kg N eq	0.26	0.0598	0.165	0.035	8.18E-05	0.0001
Freshwater ecotoxicity	CTUe	17.2	15.66	1.29	0.26	0.0016	0.0014
Land use	kg C deficit	2.23	2	0.011	0.123	1.36E-05	0.0983
Water resource depletion	m3 water eq	0.025	0.0162	0.008	0.0006	9.54E-06	1.11E-05
Mineral, fossil & renewable resource depletion	kg Sb eq	1.23E-13	0	9.37E-14	2.91E-14	1.07E-16	9.10E-17

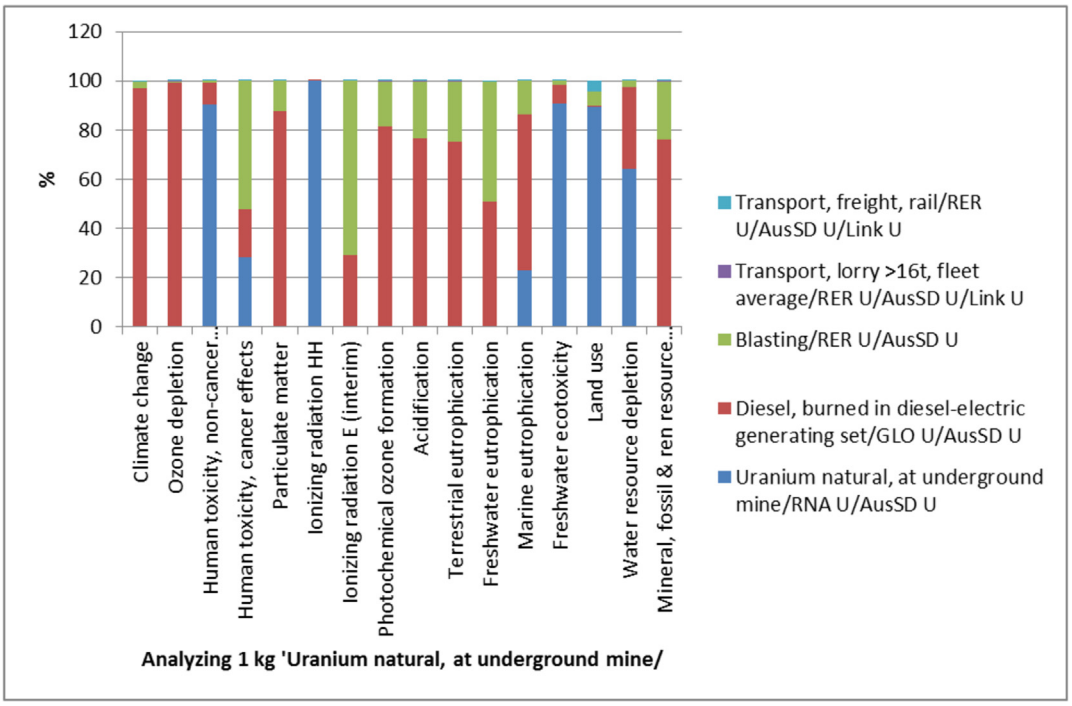


Fig. 11. Comparative life-cycle assessment results - underground mining.

cancer), marine eutrophication, freshwater eco-toxicity, land use, and ionizing radiation.

5.3.3. In-situ leaching

Table 8 summarizes the quantified results of LCIA for in-situ-leaching mining process. Among the 14 major impact categories presented in the table, ionizing radiation has the most significant impact, at 989.87 kBq U235 eq. The second-most impactful category is human toxicity (non-cancer effects) at 5.71E-06 CTUh followed by human toxicity (cancer effects) impacts up to 6.27E-07 CTUh. From the other significant categories, the climate-change effect is 73.89 kg CO_2 and water resources depletion impact is 0.9318 m^3 water eq.

Fig. 12 illustrates the life-cycle assessment results assessed through the ILCD method for in-situ leaching mining technologies for uranium extraction. As the figure shows, uranium natural is responsible for human toxicity (non-cancer effects), ionizing radiation, photochemical ozone formation, terrestrial eutrophication, marine eutrophication, and water resources depletion. Soda powder used in the plant is responsible for climate change, ozone depletion, particulate matter, and freshwater ecotoxicity. Ethylenediamine used in the plant is responsible for climate change, ozone depletion, terrestrial eutrophication, and marine eutrophication. Inorganic chemicals affect ionizing radiation and mineral, fossil and renewable energy resources depletion.

6. Results interpretation and discussion

This section evaluates and interprets the results from the inventory-analysis and impact-assessment phase to compare among the production stages and estimate the impacts per production phase, impacts on ecosystems, environment, and human health. The life-cycle assessment can: propose a systematic evaluation of the environmental consequences, estimate the amount of emission to the water, air and soil environment in each cycle of the product or process, measure ecological effects of substances, and contrast the health and environmental effects of the same product or process in order to select the optimum method (Farjana et al., 2018d, 2018e; Mahmud et al, 2018a).

6.1. Comparative assessment of life-cycle assessment results

Fig. 13 presents a comparative assessment of the life-cycle environmental impacts from open-pit mining, underground mining, and the in-situ-leaching uranium extraction processes. Among the analysis results from 14 impact categories, in-situ-leaching uranium extraction has a greater impact than open-pit mining and underground mining throughout 13 impact categories, which excludes ionizing radiation. For ionizing radiation, the underground mining method is the most detrimental process. Underground mining holds the second position overall while the most sustainable uranium extraction process identified is open-pit mining. The reason behind this result is the radon-222 emission from underground mining, which is 1000000 kBq, while from open-pit mining radon-222 emission is 13000 kBq and from in-situ leaching, it is 150000 kBq. Similarly, the radium-226 discharge is 23 kBq from underground mining, while from open-pit mining radium-226 emission is one kBq and from in-situ leaching it is 0.094 kBq.

6.2. Comparative assessment of Cumulative Energy Demand method

Fig. 14 graphically represents the LCIA results from the Cumulative Energy Demand method (CED) which assessed the breakdown of the fuel used throughout the uranium extraction processes - analyzed for open-pit mining, underground mining, and in-situ leaching. The fuel inputs considered here across the system are fossil fuels, renewables, nuclear, biomass, embodied energy (lower heating values), embodied energy (higher heating values) and other energy sources. In-situ-leaching uranium extraction is the most energy-intensive process and consumes the highest amount

Table 8
Life cycle impact analysis results for in-situ-leaching mining using ILCD method.

Label	Unit	Total	Uranium natural	Diesel, burned in diesel-electric generating set	Heavy fuel oil	Ammonia, liquid, at regional storehouse	Ammonium sulphate, as N, at regional storehouse	Chemicals inorganic, at plant	Chemicals organic, at plant	Ethylenediamine, at plant	Soda, powder, at plant	Sodium chlorate, powder	Sodium chloride, brine solution	Sodium hydroxide, 50% in H_2O
Climate change	kg CO_2 eq	73.895	0	20.50	32.091	2.373	0.336	0.758	0.855	0.1229	1.50	7.84	0.31	0.066
Ozone depletion	kg CFC-11 eq	7.90E-06	0	23.73	37.063	1.538	0.088	0.652	0.333	0.338	0.13	0.28	0.06	0.005
Human toxicity, non-cancer effects	CTUh	5.71E-06	5.88	3.711	16.8	0.732	0.049	0.510	0.225	0.2862	0.87	1.19	0.05	0.226
Human toxicity, cancer effects	CTUh	6.29E-07	0.08	0.34	4.52	0.2	0.01	1.62	0.56	0.0648	0.45	49.9	0.01	0.022
Particulate matter	kg PM2.5 eq	0.11	0.22	12.9	35.6	1.3	0.13	0.26	0.20	0.021	0.83	0.49	0.07	0.00
Ionizing radiation HH	kBq U235 eq	989.8	19.1	3.05E-05	4.65E-05	1.6E-05	3.76E-07	0.0005	6.72E-06	1.42E-07	1.08E-05	1.4E-06	8.05E-08	6.54E-09
Ionizing radiation E (interim)	CTUe	4.88E-08	0	0.52	1.17	2.6	0.002	91.1	1.06	0.0217	0.02	0.204	0.002	0.0001
Photochemical ozone formation	kg NMVOC eq	1.002	12.6	27.2	5.55	0.26	0.05	0.15	0.19	0.0237	0.32	1.4	0.05	0.01
Acidification	molc H+ eq	1.468	1.22	14.9	13.3	0.36	0.04	0.28	0.13	0.0175	0.83	0.7	0.04	0.006
Terrestrial eutrophication	molc N eq	3.50	2.71	30.2	4.42	0.22	0.04	0.20	0.14	0.0305	0.97	1.7	0.05	0.01
Freshwater eutrophication	kg P eq	0.001	6.17	0.18	0.28	0.34	0.002	5.64	0.30	0.0183	4.08	0.6	0.01	0.01
Marine eutrophication	kg N eq	0.41	15.7	23.5	3.45	0.19	0.03	0.12	0.10	0.055	0.36	1.4	0.04	0.01
Freshwater ecotoxicity	CTUe	93.5	13.9	0.80	36.5	1.52	0.07	0.19	0.25	0.0328	0.09	3.4	0.06	0.001
Land use	kg C deficit	167	39.4	0.004	0.002	0.02	0.01	0.09	0.004	0.001	0.11			
Water resource depletion	m3 water eq	0.93	17.3	0.52	0.82	0.05	0.002	0.27	0.43	0.0552	1.32	2.83	0.17	0.03
Mineral, fossil & resource depletion	kg Sb eq	1.24E-11	0	0.44	1.09	0.05	0.002	97.3	0.007	0.0005	0.01	0.08	0.0019	4.7E-05

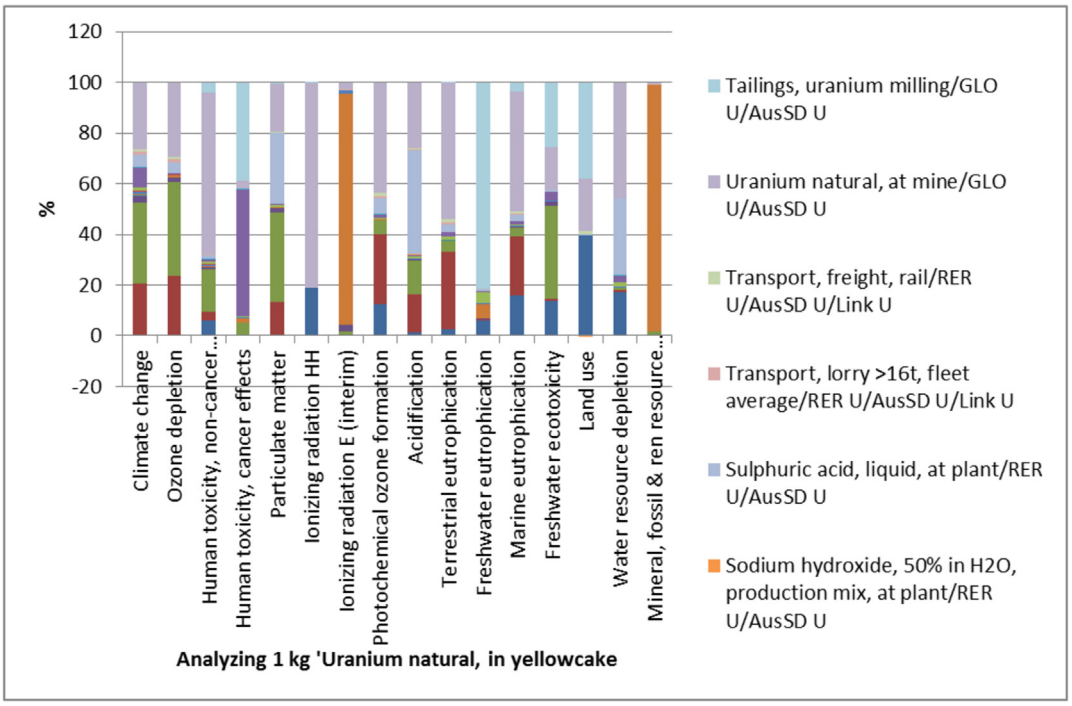


Fig. 12. Comparative life-cycle assessment results -in-situ-leaching mining.

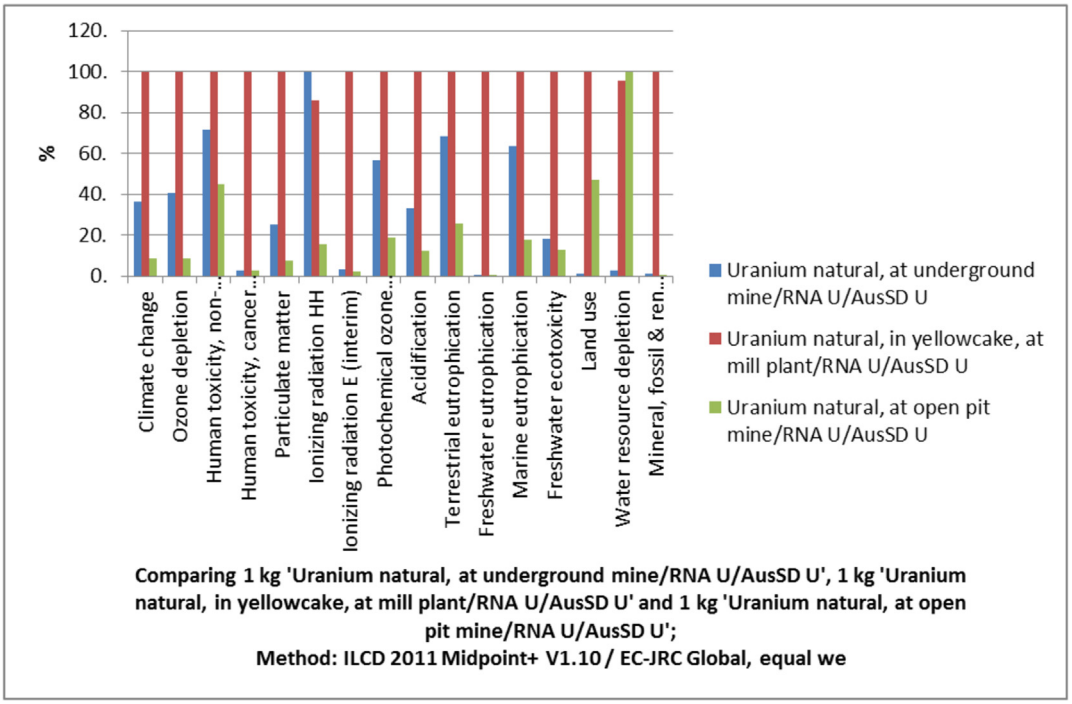


Fig. 13. Graphical representation of ILCD method analysis results.

of fossil fuels, renewables, biomass, nuclear energy, and embodied energy. Open-pit mining uranium absorbs the highest amount of energy and embodied energy and underground mining consumes the least amount of energy throughout the uranium extraction process (Schwartz and Colman, 1998).

6.3. Sensitivity analysis

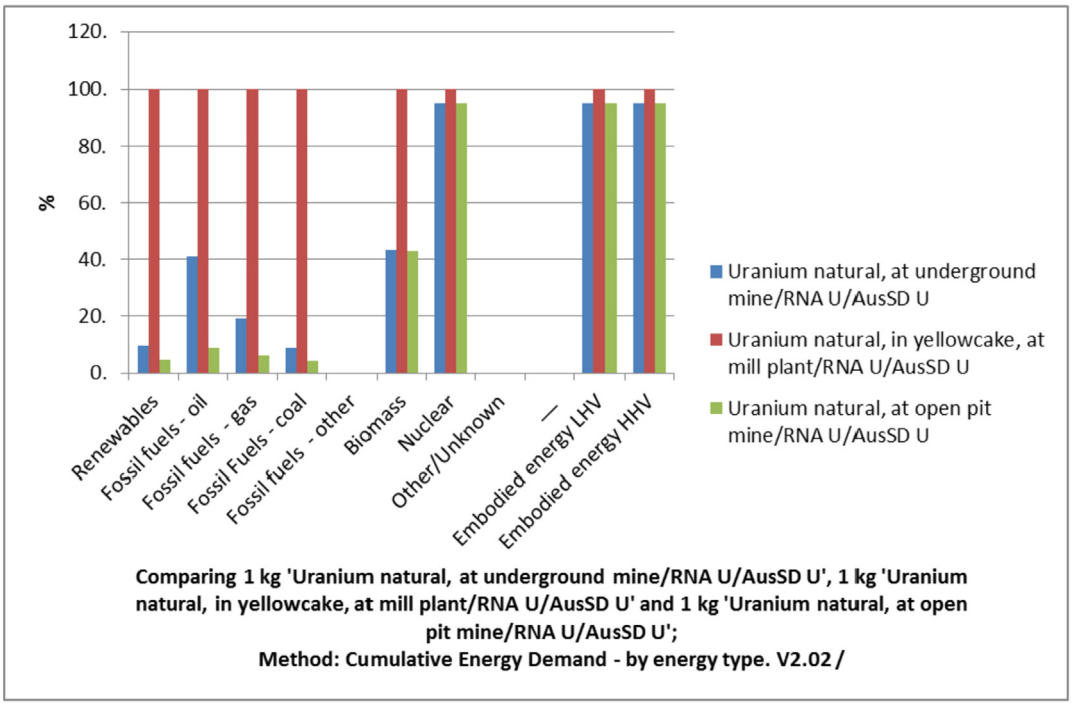
For the sensitivity analysis performed here, three different case scenarios are chosen including the base-case scenario. The details are outlined below:

Scenario 1 - base case with the required amount of diesel burned in the diesel-electric generating unit.

Scenario 2 - base case is increased by 50%.

Scenario 3 - base case is reduced by 50%.

From the sensitivity analysis results shown in Table 9, increasing the energy consumption will significantly increase the negative impacts on climate change, ozone depletion, and particulate


120.
100.
80.
60.
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20.
0.
%
Renewables
Fossil fuels - oil
Fossil fuels - gas
Fossil Fuels - coal
Fossil fuels - other
Biomass
Nuclear
Other/Unknown
—
Embodied energy LHV
Embodied energy HHV
Uranium natural, at underground mine/RNA U/AusSD U
Uranium natural, in yellowcake, at mill plant/RNA U/AusSD U
Uranium natural, at open pit mine/RNA U/AusSD U
Comparing 1 kg 'Uranium natural, at underground mine/RNA U/AusSD U', 1 kg 'Uranium natural, in yellowcake, at mill plant/RNA U/AusSD U' and 1 kg 'Uranium natural, at open pit mine/RNA U/AusSD U';
Method: Cumulative Energy Demand - by energy type. V2.02 /

Fig. 14. Graphical representation of CED method analysis results.

Table 9
Sensitivity analysis results for uranium extraction processes based on three different case scenarios.

	Open-pit mining			Underground mining			In-situ-leaching		
Label	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Climate change	90.01	100	80.02	67.37	100	34.74	90.69	100	81.39
Ozone depletion	88.92	100	77.84	66.84	100	33.69	89.39	100	78.78
Human toxicity, non-cancer effects	99.74	100	99.49	95.75	100	91.51	98.17	100	96.35
Human toxicity, cancer effects	99.39	100	98.78	91.10	100	82.21	99.82	100	99.65
Particulate matter	90.38	100	80.77	69.48	100	38.97	93.92	100	87.841
Ionizing radiation HH	100	100	100	100.	100	100	100	100	100.
Ionizing radiation E (interim)	98.94	100	97.89	87.19	100	74.39	99.73	100	99.47
Photochemical ozone formation	95.03	100	90.07	70.99	100	41.99	88.00	100	76.016
Acidification	95.96	100	91.92	72.26	100	44.52	93.03	100	86.078
Terrestrial eutrophication	96.14	100	92.28	72.59	100	45.19	86.86	100	73.72
Freshwater eutrophication	96.81	100	93.63	79.69	100	59.39	99.90	100	99.817
Marine eutrophication	95.60	100	91.21	75.95	100	51.91	89.45	100	78.901
Freshwater ecotoxicity	99.70	100	99.41	96.38	100	92.77	99.59	100	99.194
Land use	99.99	100	99.99	99.73	100	99.47	99.99	100	99.995
Water resource depletion	99.97	100	99.95	85.81	100	71.62	99.73	100	99.476
Mineral, fossil & ren resource depletion	94.95	100	89.91	72.42	100	44.84	99.77	100	99.558

matter. The sensitivity remains unchanged in ionizing radiation, human toxicity (cancer and non-cancer effects) and most of the categories of resources. Thermal energy or electrical energy generation sources could be replaced by renewable energy resources, nano-power generation sources, or by increasing energy efficiency measures reduce the fossil fuel consumption to reduce the harmful and impactful emissions to the environment: regarding land, water, soil and air (Farjana et al., 2018c, 2018b; 2018a; Hisan et al., 2018; Mahmud et al., 2018b; Parvez Mahmud et al., 2018).

7. Conclusion

Life-cycle inventory data analysis and impact assessment were carried out in this paper using the commercial software SimaPro version 8.5 using the ILCD and CED methods. The LCIA analysis results show that the underground mining method has greater radioactivity effects than open-pit mining and in-situ-leaching mining due to higher quantities of radon-222 and radium-226 emissions. In other major impact categories such as human health (cancer and non-cancer), ecotoxicity, resources, and climate change, the in-situ leaching method has severe environmental impacts. Due to the higher amount of energy consumption and inorganic and organic chemical consumption (illustrated by the LCIA assessed through the CED method), in-situ-leaching mining is more detrimental to the environment than others, though reducing the energy consumption can reduce the environmental effects to a moderate extent, which is further clarified by the sensitivity analysis reported in this paper. The limitation of this study is that the energy generation in in-situ leaching mining is from heavy fuel oil and diesel electric generating unit which makes the higher impact analysis results. The operating mines where natural gas is used as the energy generation source for in-situ leaching, all the impacts

will be signficantly lower and can be considered as sustainable. Usage of natural gas was not considered in this current study due to lack of availability of sufficient data source. If natural gas was considered here, the results would have significant variation which can ensure greater sustainability during in-situ leaching mining process. The outcomes of this research provides valuable insights in identifying the most sustainable uranium extraction process among all the significant impact categories studied such as climate change, ionizing radiation, human toxicity (cancer), and human toxicity (non-cancer) effects. In future, research should be carried out to model and validate appropriate datasets for process and mine specific uranium extraction methods.

Nomenclature

Term	Description
kg CO_2 eq	Carbon dioxide equivalent
kg CFC-11 eq	Ozone Depletion Potential OZDP kg CFC-11 eq
CTUh	Comparative Toxic Unit for human
kg PM2.5 eq	Human Health Particulate
kBq U235 eq	a decay of 1000 U 235 nuclei per second
CTUe	Comparative Toxic Unit for ecosystems
kg NMVOC eq	Non-methane volatile organic compounds (NMVOCs) equivalent units
molc H+ eq	Acidification units
molc N eq	Terrestrial eutrophication
kg P eq	Freshwater eutrophication kg P eq
kg N eq	Eutrophication potential for air emissions
kg C deficit	kilograms of carbon deficit
m3 water eq	Volume of water
kg Sb eq	Abiotic depletion equivalent

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